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WHAT WE KNOW ABOUT COMETS[1]

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THE startlingly sudden appearance of some great comets, the rapid growth of others to enormous sizes and their equally rapid disappearance have naturally excited the interest and, only too often, the fears of the human race. We are removed less than two centuries from the long-prevailing theological view that comets are flaming fire-balls hurled at the earth by an angry God, to frighten and punish a sinful world. Up to the time of my childhood the opinion was widespread among civilized peoples that comets are the forerunners of famine, pestilence and war. Did not the great comet of 1811 herald the war of 1812; the comet of 1843 the war of 1846; and Donati's comet of 1858 our Civil War? Even in the twentieth century the fear that a comet may collide with the earth and destroy its inhabitants comes to the surface, here and there, every time a comet is visible to the naked eye. This fear is not lessened by the highly sensational descriptions of such encounters by professional writers who have that little knowledge which has been called a dangerous thing.

The earth has undoubtedly encountered comets' tails scores and scores of times since the advent of man, and with no baneful effects; and in the light of present-day knowledge of the structure and chemical composition of comets there is no danger whatever that our atmosphere will be poisoned by such an encounter. It is true that a collision between the earth and the head of a comet *could* happen, but we see no reason to question the accuracy of the estimates made by mathematical astronomers that such encounters will not occur more than once in fifteen or twenty million years, on the average! It is by no means certain that such an encounter, should one ever occur, would be a serious matter for the earth. Its effects might be confined to a brilliant shower of meteors, such as the peoples of the earth have observed many times. Geologists are of the opinion that the outcropping strata

[1] Retiring address of the first president of the Pacific Division of the American Association for the Advancement of Science. San Diego, August 9, 1916.

of the earth which they have been able to study have required a period of approximately 100 million years for their formation. These strata, embracing the entire land area of the earth, have given only one bit of evidence that the earth's surface has been affected by a collision with an outside body. In central Arizona is a cup-shaped hole-in-the-ground, about three quarters of a mile in diameter and several hundred feet deep which has been formed, with little doubt, by the descent of a great meteorite, or of a great cluster of small meteorites: thousands of small iron meteorites have been found in and around the hole, and there are no evidences of volcanic activity in the neighborhood. Geologic and geographic surveys of the earth have revealed no other case of collisional effects[2] in the records of a hundred million years. Man himself has lived upon the earth certainly many tens of thousands of years, and there are no traditions extant concerning injuries to earth or to man from comets. Why then should anybody worry about possible injury from a comet in his short span of three score years and ten?

The answer to our first question, where do comets come from, involves the question of their relationship to the solar system and to the great stellar system. It is essential that every auditor should understand certain prominent features of the solar and stellar systems; and, at the risk of repeating what many members of the audience already know, I shall devote a few lines to a description of these systems.

Widely scattered throughout a great, but finite, volume of space occupied by our stellar system are tens of millions of stars. It is estimated that our largest refracting telescopes could show us about seventy million stars, and that the reflecting telescopes could photograph possibly two or three times as many. Our own sun is just one of these scores of millions of stars. It seems very large, very bright and very hot because we on the earth are relatively close to it. It is our own star. Revolving around it are many planets, of which our earth is one. Probably the other stars in many cases, possibly in all cases, have planets revolving around them in the same way. We do not know that this is a fact because the nearest star, excepting our own star, is so far away that we should require telescopes at least twenty-five feet in diameter to see planets revolving about it, even though such planets be as large as Jupiter and Saturn, the largest planets revolving around the sun.

Now the sun and its planets and their moons are the chief members of an orderly system which we call the solar system. Ninety-nine and six sevenths per cent. of all the materials in the solar system is in the sun, and only one seventh of one per cent. is divided up to form the planets and their moons: Mercury, Venus, the Earth and its one moon, Mars and its two moons, the more than 800 minor planets which move

[2] Neglecting the insignificant cavities produced by isolated small meteorites.

in the zone lying just outside the orbit of Mars, the giant planet Jupiter and its nine moons, the planet Saturn with its ring system and its nine moons, the planet Uranus and its four moons, and the outermost-known planet Neptune and its one moon.

It is a most interesting fact that all of these planets revolve around the sun in the same direction, which astronomers have agreed to call from west to east, or in the "direct" sense. Motion from east to west is called "retrograde."

Another remarkable fact is this: the orbits of all these bodies lie nearly in the same plane. If we call the distance from the sun to the earth unity, then the distance from the sun to the outermost planet, Neptune, on the same scale is thirty units, and the diameter of the solar system on that scale is sixty units. If we had a great box sixty such units in diameter and only one unit in thickness the solar system could be placed within this box and all of the eight major planets and their moons and nearly all of the minor planets would perform their motions within the box. A few of the minor planets would dip a little out of the box, above or below.

The solar system is very completely isolated in space. If the distance from the sun to the earth is one and from the sun to Neptune thirty, then the distance to the next nearest star of which we have any knowledge, Alpha Centauri, is 275,000. A ray of light traveling with a speed of 186,000 miles per second would travel from the sun to the earth in eight and one third minutes, to Neptune in four and a half hours, but it would require four and a half years to reach the sun's nearest neighbor, Alpha Centauri. The stars in the great stellar system are distributed more or less irregularly, but their average distance apart is of the order of six or seven or eight light years.

All of the stars are in motion, and our own star, the sun, is no exception to the rule. It is one of the well-established facts of astronomy that our solar system is traveling through space in the general direction of the boundary line between the constellations Lyra and Hercules with a speed of approximately twelve and one half miles per second.

It is well known that the orbits of our planets are ellipses which do not differ greatly from the circular form. The comets, on the other hand, move in very elongated orbits around the sun. The orbits of some comets are easily recognized as ellipses, but for the great majority of comets the orbits differ but little from the parabolic form. The parabola, as many of you know, is on the dividing line between ellipses and hyperbolas. The ellipse is a closed curve, and a comet moving around the sun in an elliptic orbit should return again and again to the neighborhood of the sun; but a comet following a parabolic or hyperbolic path, subject merely to the attraction of the sun, can pass through the vicinity of the sun only once, for the parabola and hyper-

bola are not closed curves, and the branch upon which the comet approaches the sun and the branch upon which the comet recedes from the sun never come together, no matter how far out from the sun they be drawn.

There have been two hypotheses as to where the comets come from. Sir Isaac Newton thought of them as moving in elongated ellipses. It

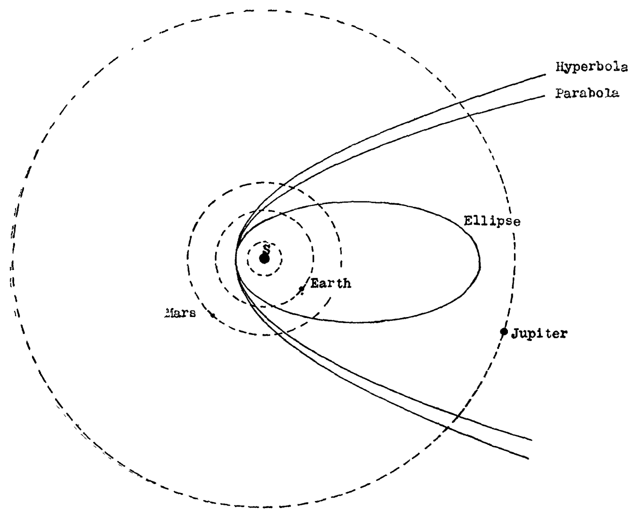

FIG. 1. CHARACTERISTIC FORMS OF ORBITS.

was the view of Immanuel Kant 160 years ago that comets are bona fide members of the solar system, just as the earth and Neptune are: that their orbits are all ellipses, but very elongated ellipses. He said that the comets travel out a great distance from the sun, but that they must eventually return because they are moving in ellipses. Kant's view of the subject was essentially a mere opinion, though the opinion of one of the greatest philosophers of all time, who gave careful consideration to every known fact. Up to Kant's day, and for many decades later, comet observations were crude in comparison with present-day standards. Most comets were observed for only a few weeks, and the true characters of their orbits could not be affirmed.

Half a century later the great Laplace championed the view that the comets belong to the stellar system and not to the solar system; that comets are travellers through interstellar space; that the wanderings of a chance few comets bring them within the sphere of influence of our sun; and that we see those which come into favorable position near the earth. Halley's celebrated comet was the only one then known to return again and again to the region of the sun, and it was thought to be a captured wanderer. In Laplace's time also the comets were still inaccurately observed, over short periods of time, and in nearly

every case a parabola seemed to represent their motion satisfactorily. This Laplacean view that comets are wanderers through the great stellar system and are only chance visitors to the solar system was the prevailing one throughout the nineteenth century. Evidences to the contrary began to appear as early as 1860, but so firmly rooted was the hypothesis that only in the twentieth century have astronomers in general been convinced that the comets are members of the solar system. Several lines of evidence, all in good agreement, have brought us to this conclusion.

1. Since the solar system is traveling through the stellar system in the direction of the constellations Lyra and Hercules, with a speed of twelve and a half miles per second, if comets come in from interstellar space we should *meet* more comets coming from the Lyra-Hercules direction than there are comets *overtaking* us from the opposite part of the sky, for precisely the same reason that if we are traveling very rapidly by automobile from San Diego to Los Angeles we should meet more autos than would overtake us and pass us. Now the comets do not show that preference. As early as 1860 Carrington studied the directions of approach of all the comets, 133 in number, which up to that time were considered to have parabolic or hyperbolic orbits. He found that only sixty-one[3] of these comets met the solar system, so to speak, whereas seventy-two[3] comets overtook us—extremely strong evidence that the comets are traveling along with us, just as all of our planets are traveling with the sun while revolving around it. Many later astronomers, especially Fabry, using the more plentiful and more accurate data now available, have confirmed this conclusion that there is no tendency for comets to meet us, as we rush through interstellar space, rather than to overtake us. It is a fact, however, that the observed comets have not had their directions of approach distributed uniformly over the surface of the sphere. Their deviations from reasonable uniformity appear to be due in small measure to a preference of comets to travel in planes making small angles with the ecliptic, with motion around the sun from west to east as in the case of the planets; but the chief discrepancies arise from the heterogeneous circumstances under which comets are discovered.

Nearly all discoveries of comets made by means of telescopes prior to forty years ago were made in the northern hemisphere, at observatories situated in latitudes north of $+40°$. The southern hemisphere is still very much in arrears in the matter of comet discoveries, though the discrepancy is not now so great as it once was.

There is more searching for comets in the northern hemisphere during the northern summer and in the southern hemisphere during the southern summer than in their respective winters. There is also

[3] The disparity in the numbers is thought to be purely accidental.

a better chance for northern observers to discover comets when the sun is farthest north in June and for southern observers when the sun is farthest south in December. These facts lead to the discovery of comets, prevailingly, which come to perihelion in certain favored regions; that is, in the regions of the sky where the earth is at those times.

It is advantageous at this point to call attention to other sources of lack of homogeneity in comet data.

Prior to the invention of the telescope, three centuries ago, about 400 comets had been made matters of historical record. These were naked-eye objects which forced themselves upon the attention of observers. They were the especially large comets which came close to the earth or to the sun. They were imperfectly observed, and for only a small proportion of them do we know even their approximate orbits.

Since the invention of the telescope, about 450 comets have been discovered, and the half of these have been found in the last fifty years. What we may call the golden age of comet discovery included the two decades, 1888 to 1908, when 100 comets, an average of five per year, were discovered. Four American observers, Swift, Brooks, Barnard and Perrine, announced the arrival of thirty-seven of these 100 comets.

All of the early comets were visible to the naked eye. Only a small fraction of recent comets, perhaps one in four, become bright enough for the unassisted eye to see the head, and perhaps one in eight or ten for the unassisted eye to see the tail. Comet orbits have become increasingly accurate, partly because of greater telescopes, which enable these bodies to be more accurately observed and observed through longer arcs of their orbits.

2. Another decisive argument for the theory that comets are at home in the solar system is this: Schiaparelli showed in the early '70's that, owing to the sun's motion through the stellar system, if the comets come from distant interstellar space, a very large proportion of them should move around our sun in hyperbolic orbits, and many of these orbits should be *strongly* hyperbolic. Schiaparelli's conclusions have been confirmed and extended by several mathematical astronomers, notably by Louis Fabry. Fabry concluded: If the sun travels through the stellar system and the comets come to the sun from interstellar space, then the comets should all move in hyperbolas—differing from the parabola the more as the velocity of the sun through space is the greater.

What are the facts of observation? Of 347 comet orbits fairly well determined

(*a*) 60 are certainly elliptic;
(*b*) 275 are approximately parabolic;

(*c*) 12 or fewer are slightly hyperbolic;
(*d*) None are strongly hyperbolic.

Now it has been shown by Thraen, Fayet and Fabry in the last two decades that several of the twelve orbits thought to be hyperbolic were not really so, but that they owed their reputations to poor or insufficient observations, or to errors in the computations, and that all of the genuine hyperbolas save one acquired their hyperbolicity after the comets concerned came under the disturbing influences of our planets. Five years ago Strömgren was able to show that the one outstanding hyperbolic orbit was caused, in the same way, by the disturbing attractions of the planets. The original, undisturbed orbit of every one of the so-called hyperbolic comets was, therefore, an ellipse. Fayet has further shown that a very great majority of the orbits which had been observed to be sensibly parabolic when the comets were near the planets and sun were clearly elliptic when the comets were still far out from the sun; that is, as these comets, moving in elliptic orbits, came in toward the planets and sun, the attractions of the planets made their orbits approach closely to the parabolic form. There is no reason to doubt that far out in the domain of the sun the comets all approach in elliptic orbits; but that when the attractions of one or more of our planets upon them become appreciable, some of the orbits are changed into shorter ellipses, others are changed into ellipses so long that it is difficult to distinguish them from parabolas, and many orbits are changed to the hyperbolic form. Those comets whose orbits are thus thrown into the hyperbolic form will leave the solar system and travel out through the stellar system.

3. A statistical study of comet orbits made by Leuschner a decade ago bears upon this question. He found that prior to 1755 ninety-nine per cent. of all comets were *said* to move in parabolic orbits, but that only fifty-four per cent. of comets between 1846 and 1895 were *said* to move in orbits approximately parabolic; and, secondly, that of comets under observation less than 100 days, sixty-eight per cent. were *said* to be parabolas, whereas of those observed from eight months to seventeen months, only thirteen per cent. have orbits approximately parabolic. These facts point to the conclusion that when comets are observed inaccurately, as of old, and in only a short section of their orbits, parabolic orbits satisfy the observations within the limits of the errors unavoidably attaching to those observations; but that when comets are observed accurately and for a long stretch of time, nearly all are found to be moving in ellipses. Most of the ellipses are of course extremely long ones.

If comets starting substantially at rest came from a very great distance away from our sun, say one hundredth the distance of the nearest star, which we think is decidedly within the sphere of our sun's attrac-

tion, they would move in ellipses so elongated that we could not hope to distinguish them from parabolas. Their periods of revolution would be nearly one hundred and fifty thousand years. Yet they would be members of our solar system, subject to the sun's attraction, and unless disturbed by some other body or bodies, they would return again and again to the center of the system.

The work of Carrington, Schiaparelli, Fabry, Fayet, Strömgren and Leuschner and of many others has left no room for doubt that comets are bona fide members of our solar system. The materials composing the great majority of comets spend most of their time in regions far removed from the sun and its planets, as our little distances in the planetary system go, but close to the sun in terms of the magnificent distances which separate our sun from the other suns. They are moving in closed orbits around our sun and traveling through space along with our sun.[4]

Besides the comets which go out on extremely elongated orbits to great distances from the sun, there are about fifty elliptic comets which

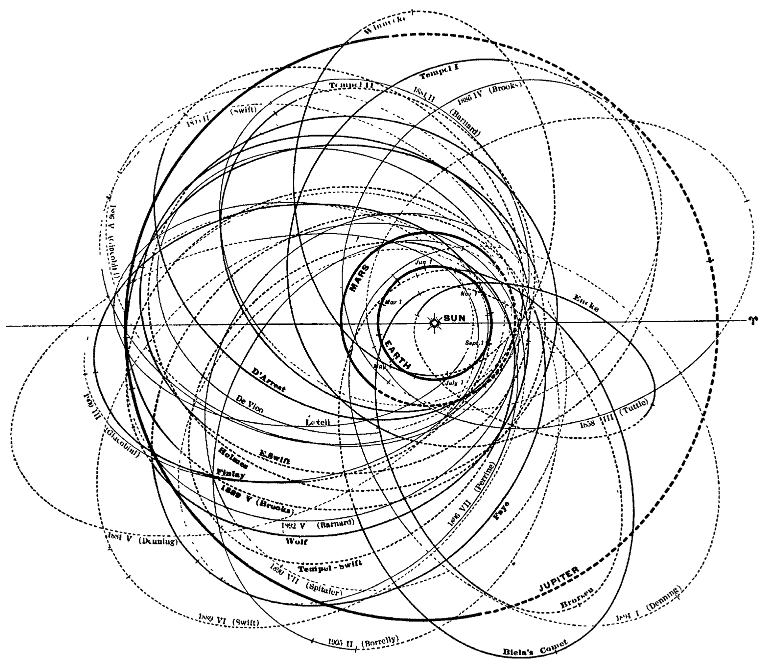

FIG. 2. JUPITER'S FAMILY OF COMETS (up to 1893).

[4] Those who would like to look more thoroughly into this question are strongly advised to read Schiaparelli's paper on "Orbites cométaires, Courants cosmiques, Météorites," in Bulletin Astronomique, vol. 27, pp. 194–205 and 241–254, 1910. It embodies some points of view slightly different from those presented by me. The technical contributions by Fabry, Fayet and Strömgren are extensive and of a high order of merit; and students of comets cannot afford to neglect them.—W. W. C.

are closely related in one sense to some of our planets. About three dozen are in the so-called Jupiter-family of comets. The orbits of all those discovered up to 1893 are represented in Fig. 2. It is seen that the outer parts of all of them—the aphelia—are in the vicinity of Jupiter's orbit. Similarly, there are a few comets related to Saturn's orbit, a few to the orbit of Uranus, and six comets to the orbit of Neptune, one of the latter being Halley's comet. The Jupiter comets have periods lying between three and nine years, and the Neptune comets complete their circuits in from sixty to eighty-one years.

What has been the history of these short-period comets? H. A. Newton and other investigators have shown that it would be impossible for great numbers of comets, such as have been observed, to move through the solar system, without a certain proportion having their orbits changed into short-period elliptic orbits. It is the accepted view that the short-period comets have been captured, so to speak, by the combined attractions of the sun and one of the planets in each case. The chances of capture by the planets are greatest when the approaching bodies are moving in orbits which lie in planes most nearly coincident with the plane of the planetary system, and when their motions around the sun are from west to east. Newton's analysis of the problem led to the conclusion that five or six times as many captured comets should move in the direct sense, west to east, as in the retrograde sense, east to west. Now the only comets with periods less than 100 years which are revolving around the sun in the retrograde direction are Halley's comet, period seventy-six years, and comet 1866I, period thirty-three years. The three dozen members of the Jupiter family revolve from west to east without exception. That the motion in the short-period orbits is so universally from west to east finds the most probable explanation in the view that the cometary materials, when they were farthest from the sun, long before they approached the region of the planets and the sun, already had a slow motion from west to east, the motion of the parent mass of matter from which the solar system itself was developed. The French astronomer, Faye, on the assumption that comets have originated in the outer parts of a rotating mass which has developed into the solar system, came to the conclusion that comets should move prevailingly in the direct sense when their orbit planes do not differ greatly from the orbit planes of the planets, but that those whose orbit planes make great angles with the plane of the solar system should show no preference for the direct over the retrograde motions. These theoretical results are in good accord with the observed facts.

Our second question is, what are comets?

Comets have certain characteristic features:

1. There is always a head, or coma as it is sometimes called, a shin-

FIG. 3. HALLEY'S COMET, MAY 1, 1910; head and beginning of tail.

ing mass of hazy, nebulous matter. The head is sometimes circular in outline, more frequently elliptical or nearly so, but again it is oval on the edge facing the sun and it merges insensibly into the tail on the side opposite the sun (Figs. 3, 4 and 5). The sizes of comet heads vary enormously. One less than 10,000 miles in diameter would be most unusual and generally would escape discovery. The head of the great comet of 1811 was at one time more than a million miles in diameter. The head of the great comet of 1882, which many of us

enjoyed seeing, was for a long time about 150,000 miles in diameter. It is a curious fact that the heads of comets in general contract in size as they approach the sun and expand as they recede from the sun. Encke's periodic comet, which has been observed on many returns, frequently had a diameter of 250,000 miles or more when the comet was at a great distance from the sun, whereas the diameter of the head reduced to 10,000 or 15,000 miles when the comet was nearest the sun.

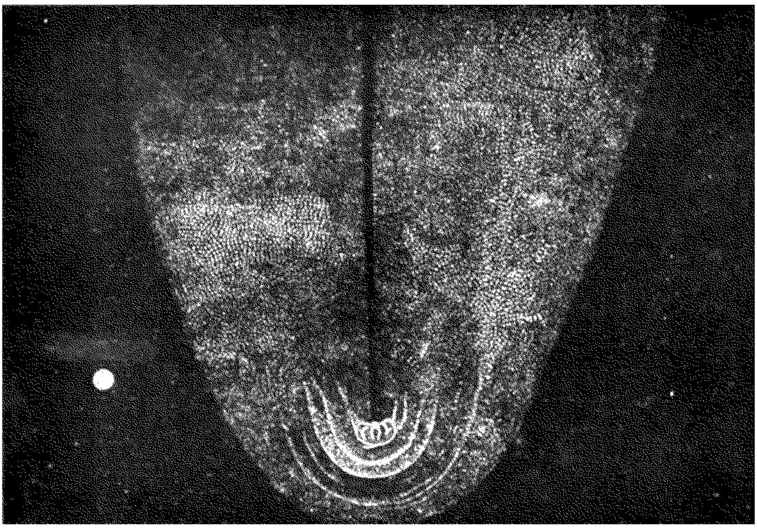

FIG. 4. DONATI'S COMET, 1858 OCTOBER 5; head and beginning of tail; brilliant stellar nucleus near center of head; envelopes surrounding nucleus on side toward the Sun. White circle to the left represents comparative size of the Earth.

Before the disappearance into distant space the head resumed its original dimensions. A satisfactory explanation of the contraction and expansion of the heads of comets has not been found.

2. Near the center of the head of the comet there is usually a brilliant, star-like point which we call the nucleus (Fig. 4). This is the point upon which accurate measures are made when it is a question of determining the position and the orbit of the comet. In general the nuclei are most sharply defined for those comets which have come in from great distances upon orbits nearly parabolic, and the nuclei are frequently hazy, poorly defined, and sometimes entirely lacking, in the comets composing Jupiter's comet family. Occasionally there is a double, a triple, or a quadruple nucleus, a division undoubtedly connected with the disintegration or breaking up of the comet into smaller masses. The size of the nucleus varies greatly, apparently from a few miles up to several thousand miles in diameter.

3. Most comets have tails. They frequently develop to enormous

dimensions. When a comet is observed at a great distance from the sun, only the head and nucleus are usually visible. The tail develops with close approach to the sun. The tail of the comet of 1882 was at one time more than 100 million miles in length; that of 1843 was at one time 200 million miles. As comets recede from the sun, the tails diminish in extent and usually disappear long before the head and nucleus are lost to sight. Several of the Jupiter comets do not have

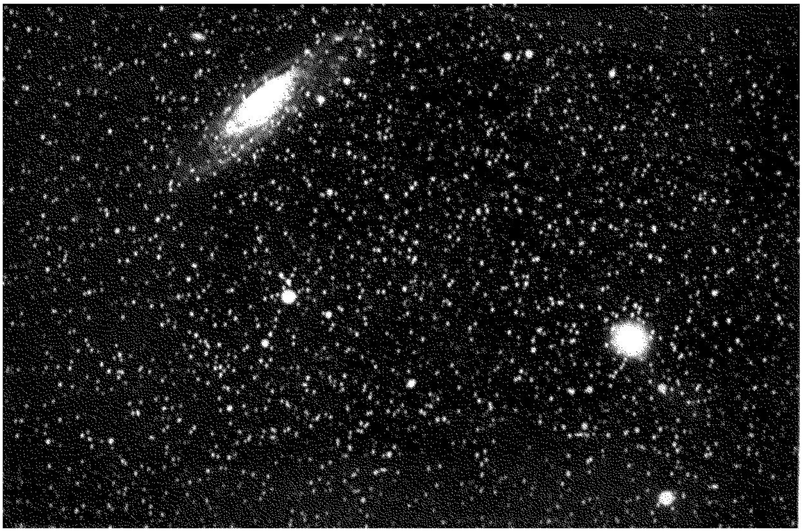

FIG. 5. HOLMES'S COMET OF 1892; no tail was visible in the telescope; long-exposure photographs (Barnard, 3 hours, 1892 Nov. 10) recorded an extremely faint tail extending down to lower right corner of the picture. The great spiral nebula in Andromeda was recorded on the photograph—upper left corner of picture.

visible tails (Fig. 5). They appear not to possess in abundance the materials which go to form comets' tails.

4. When comets approach relatively close to the sun the heads frequently throw off a series of concentric shells or envelopes. The materials composing these envelopes appear to be expelled from the head and toward the sun at high speed, but these speeds of approach to the sun seem to be gradually overcome and the materials turned away from the sun to assist in forming the tails (Fig. 4).

The tails of comets, it is well known, point away from the sun. However, the popular view that they point *exactly* away from the sun is seriously in error. In general they lag behind the line passing through the sun and the comet's head (Fig. 6). There can be no doubt that they point away from the sun because of some repulsive force, originating in the sun, which acts upon the minute dust particles or gas molecules released from the comet's head. It takes time for these particles to travel out millions of miles from the head, and,

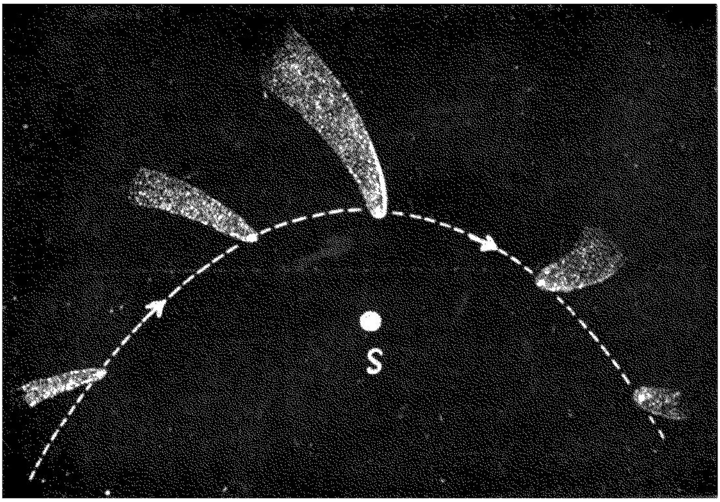

FIG. 6. COMETS' TAILS LAG BEHIND THE LINE JOINING THE SUN (S) AND THE COMETS' NUCLEI. Orbital motion is carrying the nucleus of the comet to the right.

while they are moving out, the head is moving forward in its orbit. The nucleus obeys the gravitational attraction of the sun absolutely, so far as observation has gone, and we have no reason to suspect that it is subject to an appreciable repulsive force. The particles composing the outer regions of the head and the particles composing the tail are doubtless attracted by the gravitation of the sun and are at the same time driven away by the repulsion of the sun. What the particles will do under the action of the two opposing forces depends upon the ratio of these forces. If the repulsive force is vastly stronger than the attracting force the particles will travel out from the head with great and increasing speed and form a tail pointing nearly away from the sun; that is, it will lag behind very little. If the attracting and repelling forces acting upon another group of particles are not very unequal those particles will form a second tail having considerable lag. If the repulsive force is very weak with reference to the sun's attractive force upon a third group of particles, they will form a short tail that lags very far behind. The forms and

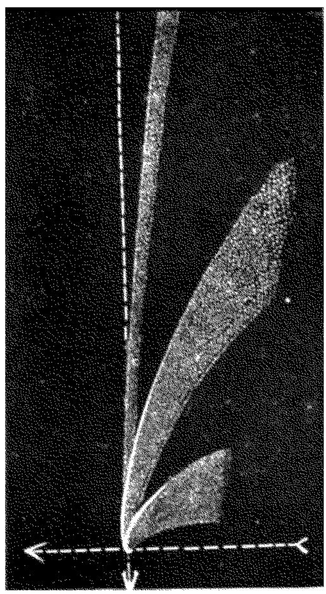

FIG. 7. DIAGRAM ILLUSTRATING THE THREE PRINCIPAL TYPES OF TAILS OF COMETS. Orbital motion is carrying the nucleus to the left. The Sun is below.

positions of comet tails were studied extensively by Bredichin, who found that there were three classes of tails, corresponding to three fairly definite ratios of repulsive to attractive forces, as indicated by three different degrees of lagging behind the line joining the sun and the head (Fig. 7).

Bredichin determined that the long slender tails, observed in a few comets, which lag behind only slightly are the result of a repulsive force twelve to fifteen times as intense as the attractive force. He found another class of comet tails, of medium lag, for which the repulsive forces were from 2.2 to 0.5 times the attractive forces. Another class of tails, short and bushy, with very strong lag, were explainable on the assumption that the repulsive forces were relatively weak, from 0.3 to 0.1 of the attractive forces.

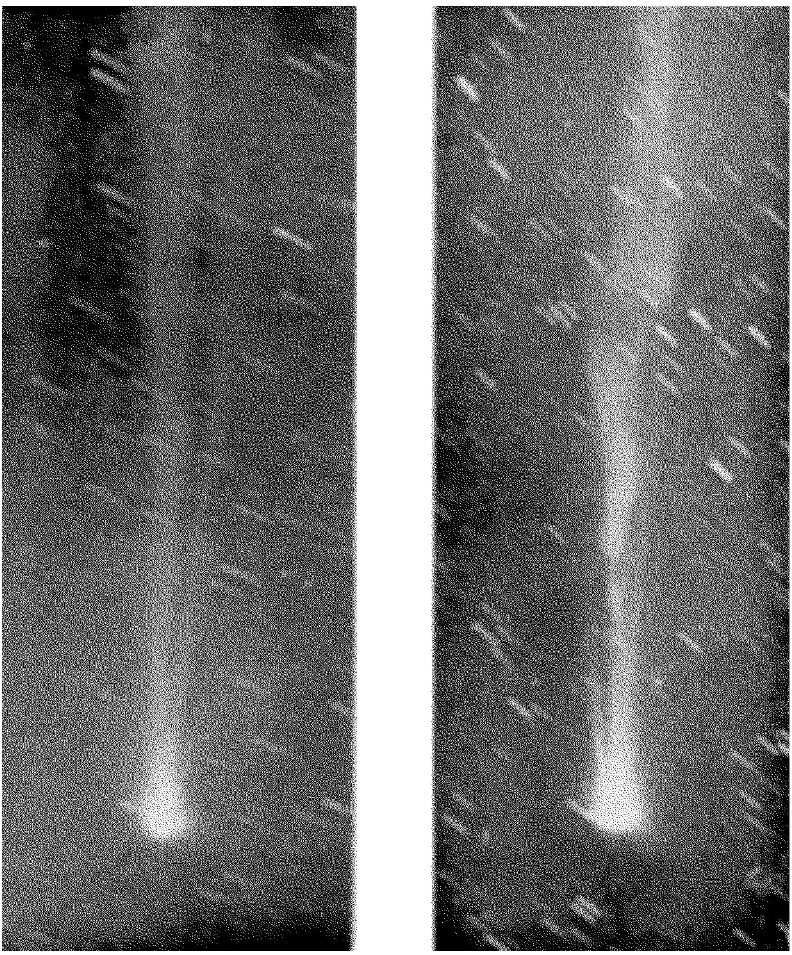

FIG. 8. COMET RORDAME ON JULY 12 AND JULY 13, 1893. The camera followed the nucleus of the comet and the stars "trailed."

In some comets only one of these three classes of tails is present, and again in one and the same comet all of the classes may be present at the same time.

That there is outward motion of the tail materials admits of no doubt. It is not uncommon for the tail materials of one night to be driven off into space, scattered and lost to sight, and for an entirely

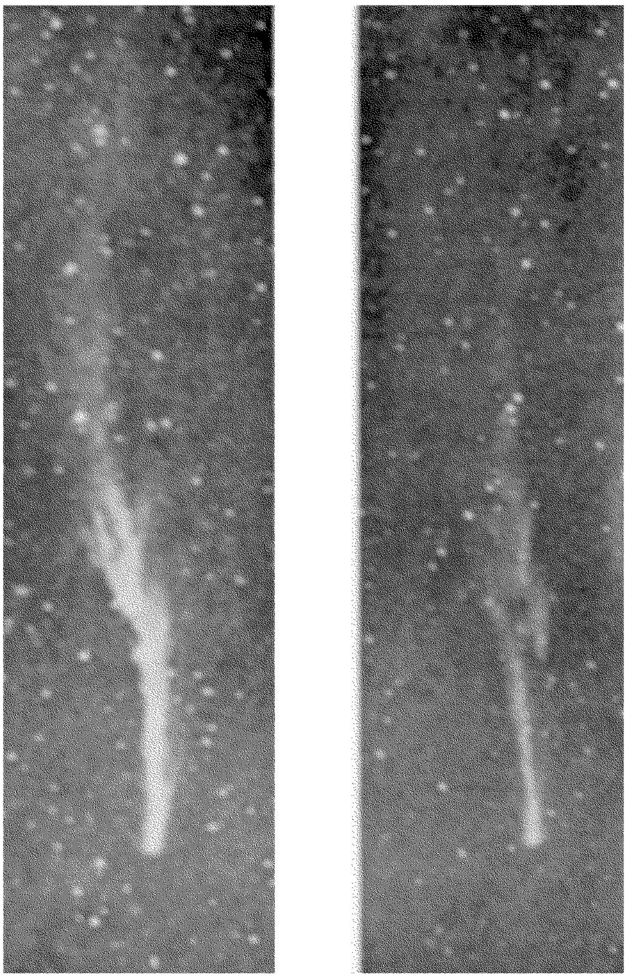

FIG. 9. COMET BROOKS ON OCTOBER 21 AND OCTOBER 22, 1893.

new tail to take its place by the following night. A comet's tail is constantly forming and moving out. The tails of comet Rordame (Fig. 8) photographed by Hussey on two successive nights, July 12 and 13, 1893, have no points of resemblance. The streamers composing the tail on one night are fairly straight, regular, and rather faint. The

tail of the following night is very much broken, there are several fairly well-defined nuclei, and it is brighter than the tail of the twelfth. Two photographs of this comet were fortunately made on the second night, with a time interval of three quarters of an hour. A comparison of the positions of the three nuclei on the two plates showed that they had moved outward from the head with great speed during the interval. The nucleus nearest the head had traveled out with a speed of forty-four miles per second, the next nucleus with a speed of fifty-two miles a second, and the one still farther out with a speed of fifty-nine miles per second. Here are two photographs of comet Brooks (Fig. 9) made on October 21 and October 22, 1893, by Barnard. The structure of the tail on the first photograph is not at all the structure on the second. The tail of the first night has been scattered to invisibility and an absolutely new tail has replaced it. The outward motion of well-defined tail structure has been measured for many comets. Here is a series of measures made by Curtis upon points in the tails of Halley's comet.

AVERAGE VELOCITIES OF RECESSION, FROM THE HEAD, OF MATTER IN THE TAIL OF HALLEY'S COMET

Date, 1910	Mean Distance from Head	Average Velocity
May 23	800 miles	0.6 miles per sec.
May 27–28	400,000 miles	8 miles per sec.
May 25–26	930,000 miles	12 miles per sec.
June 2–3	1,360,000 miles	20 miles per sec.
May 28–29	1,730,000 miles	23 miles per sec.
June 6	2,200,000 miles	27 miles per sec.
May 26–27	2,500,000 miles	24 miles per sec.
May 30–31	6,600,000 miles	45 miles per sec.
June 7–8	8,400,000 miles	57 miles per sec.

The points to be measured were not well defined, and the measures could not be accurate, but it is clear that high speeds and accelerated speeds prevailed. The tail materials start out slowly from the head, and increase their speeds with the distance from the head, as we should expect of motion resulting from the action of a continuous force which meets with no sensible resistance.

In Fig. 10 are reproductions of photographs of Halley's Comet made by Curtis on June 6 and June 7, 1910. A semi-detached part of the tail, seen on the photograph of June 6 about an inch above the head, is visible about two and a half inches above the head on the photograph of June 7. This structure was first observed by Curtis shortly after it had emerged from the central part of the head on June 4, and it was recorded on the photographs secured by a great many observatories in the following four days, as the rotation of the earth carried the comet successively into position for observation at the observatories. The times when the lower point of the structure had certain positions is

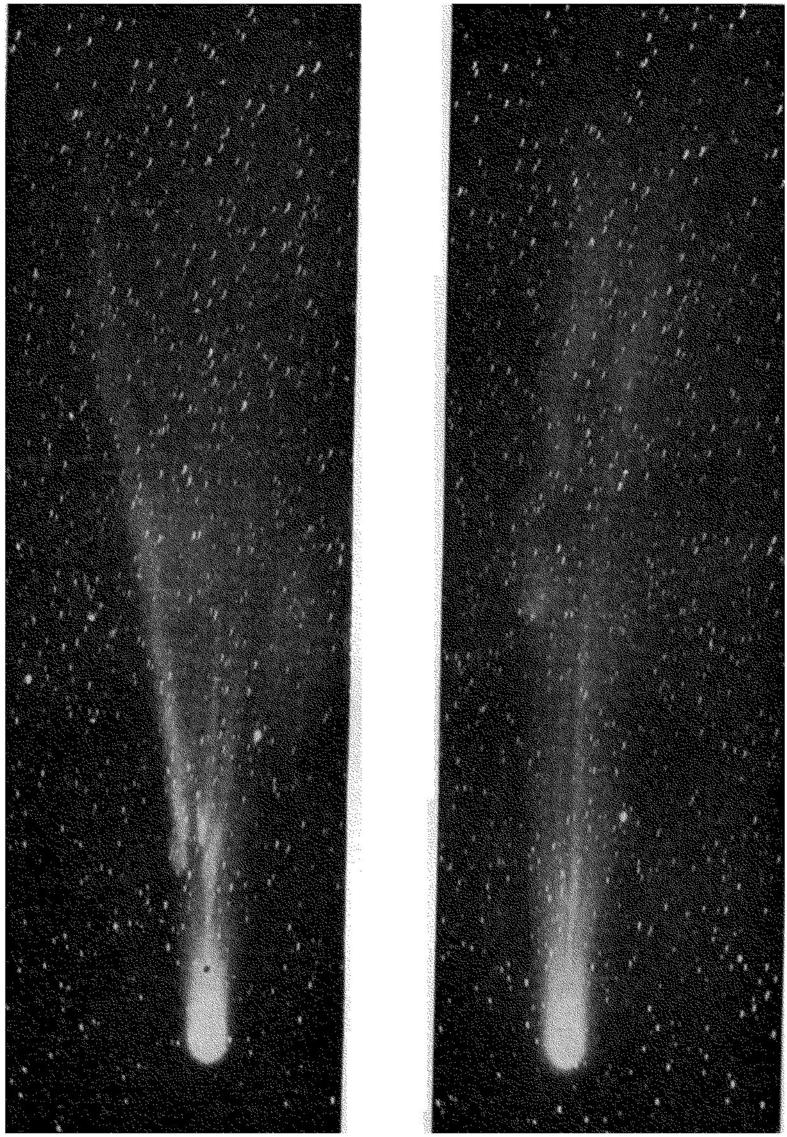

FIG. 10. HALLEY'S COMET, JUNE 6 AND JUNE 7, 1910.

indicated in Fig. 11. The tail did not seem to lag behind the position of the radius vector—the line passing through the sun and the comet's nucleus—because the observers on those days were nearly in the plane of the comet's orbit and the lag of the tail was toward the observers. The velocity with which the structure moved out in the tail was strongly accelerated with the passing of time, as may be seen from the chart.

The constant loss of materials dispelled along the tail would seem to require that comets in general grow fainter with time. This is the logical conclusion, and the observational evidence for it is undoubted in many of those comets which return again and again to the region of the sun. Nearly all of the Jupiter comets have a hazy, washed-out appearance. Several of them do not develop tails, as if their supply of tail materials had already been exhausted by expulsion as former tails. Others of them develop only very short tails, and several short-period comets have entirely disappeared. To this phase of the subject we shall return.

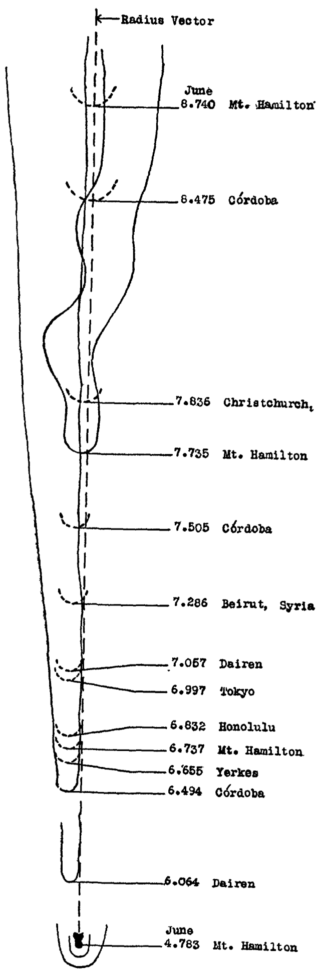

FIG. 11. SUCCESSIVE POSITIONS OF THE INNER END OF A DETACHED TAIL OF HALLEY'S COMET, JUNE 4-8, 1910.

As to the nature of the repulsive force responsible for comets' tails: It was long thought to be electrical, arising from a strong electrical field about the sun and from electric charges of the same sign on the particles composing the tail. The idea is in part purely speculative, but the giving of serious consideration to it is justified because of the fact that much of the light of comets seems to arise from electrical conditions in them. The idea may be wrong in toto, or an electric repulsive force may be one of two or more forces which are acting. It can hardly be the only force involved.

Clerk-Maxwell half a century ago, from pure theory, and Lebedew and Nichols and Hull some fifteen years ago, from experimental evidence admitting of no doubt, showed that when light energy falls upon a surface it presses against that surface; very feebly it is true, but it will cause the body pressed upon to move if that body is not too massive. In this respect light-pressure repulsion and electric repulsion should act much alike. These repulsions are effective in proportion to the surface areas of the bodies acted upon, whereas gravitation pulls those bodies with a force proportional to their masses. Now the surface of a body is proportional to the square of its dimensions, whereas gravity acts in proportion to the cube of its dimensions. The smaller a body is the more surface it has in proportion to

its mass. Electric and radiation-pressure repulsions will therefore act more efficiently upon very small particles than upon large ones. A cube of water one centimeter on each edge would be drawn by the sun's gravitational action 10,000 times as strongly as the pressure of the sun's rays falling upon that body would repel it. But a cube of water only 1/1000 of a mm. on each edge would be in equilibrium under the sun's gravitational attraction and the sun's light-pressure repulsion. A cube of water less than 1/1000 mm. would actually be driven rapidly away from the sun. The equilibrium diameter for little spheres of water, according to Nichols and Hull, is .0015 mm. Now as light energy is traveling along with a speed of 186,000 miles a second, we should expect particles of matter considerably smaller than the equilibrium size to travel away from the sun with great and rapidly increasing speeds. These speeds would be the greater for particles smaller and smaller until a certain limit of size with reference to wave-length of light is reached, after which the light would be diffracted without transmitting so large a proportion of its repulsive energy to the particles. These limits of efficiency were determined by the lamented Schwarzschild. The resistance of cometary particles is evidently also a function of the specific gravity of the particles. The figures which we have quoted are for water, density 1. We can scarcely doubt that radiation pressure is an important force, perhaps the chief force, perhaps the only force responsible for the driving out of the materials of comets' tails. Particles of solid matter or gas molecules of three different classes of sizes might be responsible for the three main classes of comets' tails. More probably materials of three different classes of density compose the three classes of tails. Bredichin called these three classes the hydrogen, the hydrocarbon and the iron tails. The atomic weights of these three substances give to their atoms or molecules about the right mobility, under equal pressure upon all, to explain the lags of the three classes of tails. Unfortunately it is far from certain that hydrogen exists in comets, and iron has been reported for only one comet.

The hoods or envelopes (Fig. 4) which form the outer strata of the heads of comets which come close to the sun are very interesting. It is the prevailing view that, when a comet approaches the sun, the solar heat falling upon that surface of the comet which faces the sun generates or liberates the gases and vapors which have been contained in or between the more solid parts of the comet; and being liberated, in effect, under pressure, the materials at first travel toward the sun with considerable speed. The sun's repulsive force acts upon these jets and, overcoming the forward motion of the materials, it eventually turns them back along the tail. Those phenomena have been observed many times.

There is a great variety of comet spectra, indicating as great a variety of cometary contents or conditions. In some cases the spectrum seems almost wholly continuous, as in Holmes's comet of 1892; in others the light when passed through the spectroscope falls almost wholly into isolated bright lines or bands, as in Morehouse's comet of 1908. Other spectra are a combination of continuous and bright-line light (Fig. 12). The spectrum of the nucleus seems to be always continuous, or continuous except for absorption lines. In some of the brighter comets the nucleus spectrum as photographed contains the well-known absorption lines visible in the sun's spectrum. These observations indicate that the nucleus is shining, at least mainly, by reflected sunlight. In most comets the continuous spectrum is too faint to let us photograph it and thus to prove the presence or absence of the solar absorption lines. The continuous spectrum in many

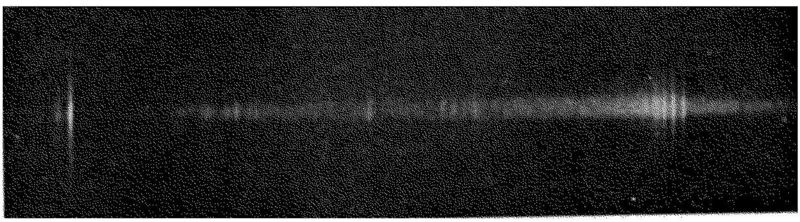

FIG. 12. SPECTRUM OF COMET DANIELS, 1907.

comets extends also to the head, or at least to the inner strata of the head. This may or may not mean reflected sunlight. It may mean some other form of luminescence which yields a continuous spectrum. The greater parts of the heads of comets and those parts of the tails of comets which are close to the heads nearly always, and perhaps in every case, give a characteristic spectrum of bright bands, which were for several decades called the hydrocarbon bands. Observations of recent years have made it probable that this spectrum does not indicate a combination of hydrogen and carbon, but that it is either one of the low-pressure carbon vapor bands or that it results from one of the compounds of carbon and oxygen, preferably from carbon monoxide. The lines and bands of cyanogen—a nitrogen compound—and of carbon are present without any question in the heads and inner tails of many comets. Several observers have reported that the so-called hydrocarbon spectrum of the heads and inner tails extends far out into the tails. This may have been true for the cases reported, but recent observations are casting doubt upon the presence of that spectrum in the outer extensions of comet tails. Improved methods of photographing comet spectra were applied to the bright comets, Daniels of 1907 and Morehouse of 1908, especially by Deslandres, Evershed and Chrétien,

with the result that their tail spectra were proved to be very different from the prevailing spectra of comets' heads and inner tails. Fowler has succeeded in duplicating the tail spectra of these two comets, in his laboratory, with remarkable agreement (Fig. 13), by photographing a cathode spectrum of carbon monoxide in a tube reduced to pressure not exceeding .01 mm. At higher pressures than this he obtained the so-called hydrocarbon spectrum, but it was not certain, and in fact it was improbable, that there was any hydrogen in the tube. The presence of carbon and nitrogen in comets is certain, the presence of oxygen is probable, and the presence of hydrogen is doubtful.

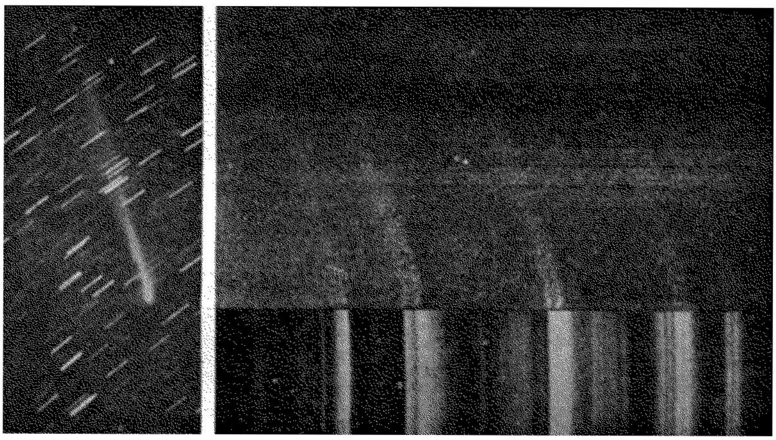

FIG. 13. (*a*) Ordinary photograph of Comet Morehouse. (*b*) Spectrum photograph of Comet Morehouse made at same time as (*a*). (*c*) Fowler's spectrum of carbon monoxide, whose principal bands match the principal spectrum images of the comet's tail.

The comets which have approached very close to the sun turned to a yellowish orange in color and remained so while in the vicinity of the sun, because the yellow light of sodium then developed strongly in them, apparently by virtue of the intense heating of the cometary matter by the sun's rays. This happened with the Wells comet of 1882, the great comet of September and October, 1882, the brilliant comet in January, 1910, and others. When the September, 1882, comet was only a few hundred thousand miles from the sun, Copeland and Lohse observed not only the sodium lines but half a dozen other bright lines which they concluded were well-known iron lines.

What is the origin of the light which gives bright lines and bands? The sodium lines certainly, and the iron lines if actually observed, were no doubt due to incandescent vapors of those elements under the intense heat of the sun. Strangely enough, when the sodium comets approached the sun, the carbon bands, which had previously been promi-

nent, disappeared entirely and remained invisible until the comets had receded to a considerable distance from the sun and the sodium lines were no longer in evidence. The carbon light could scarcely be generated by heat action, for if so the carbon bands should have been in evidence during the time that the comet was passing nearest to the sun. Much more probably the bright-line spectra of the head and tail are of electrical origin, or fluorescent. This phase of the subject is technical, and to some extent speculative, and we can not profitably pursue it further on this occasion.

A certain proportion of the light of many comets is slightly polarized. The interpretation of this phenomenon is that a fraction of the light of the heads and of the inner tails of comets is sunlight diffracted by minute dust particles or gas molecules in the comet structure.

Returning to the subject of the disintegration and disappearance of comets:

A small comet was discovered by Montaigne in 1772. A comet was discovered by Pons in 1805. A comet was discovered by Biela in 1826. Biela computed the orbit of his comet and found it to be moving in an ellipse of period six and a half years, and he proved that the three comets discovered respectively by Montaigne, Pons and himself were identically the same comet. Biela's comet was rediscovered in 1832, almost precisely in its expected place. The next return was missed because the body was not in good position for observing. It was rediscovered in 1845, when it was seen to consist of two comets moving side by side on orbits almost identical. In 1852 both comets were reobserved, but farther separated than they had been in 1845. The comet was searched for at the proper times for several later returns, but it was never seen again.[5]

Kirkwood published in 1872 a list of eight comets which had divided in a similar manner and disappeared.

A number of other comets have completely disappeared, though their orbits were very well determined.

This brings us to another interesting phase of our subject:

The Perseid meteors are with us at this time of the year. Many of them have been seen every year for several decades. They are usually most numerous on the nights of August 9, 10 and 11. Predictions concerning meteors are somewhat risky, but so faithfully have the Perseids come every August that I have no doubt an observer to-night, to-morrow night and the next night, from midnight on to daylight, would see dozens of meteors whose paths traced backwards would pass through a small area in the constellation of Perseus. In 1866 Schiaparelli computed the orbit of the Perseid meteors and noticed that it

[5] One of the components of the Biela comet may have been observed for a few hours from Madras in 1872.

was essentially identical with the orbit of Comet 1862III. Here are the elements of the two orbits.

Orbits of	Meteors of August 9, 10, 11	Comet 1862III
Perihelion passage	July 23.62	August 22.9
Longitude of perihelion	343° 38′	344° 41′
Ascending node	138 16	137 27
Inclination	63 3	66 25
Perihelion distance	0.9643	0.9626
Period of revolution	105 years?	123.4
Direction of motion	retrograde	retrograde

The difference in the two perihelion times does not mean that their orbits were different even to the minutest degree, but only that, moving on the *same* orbit, they reached the point nearest the sun at slightly different times; that is, one of the bodies traveled over the orbit a little in advance of the other. The revolution period assigned to the meteors is subject to considerable error because it is not possible to observe the paths of the meteors with great accuracy.

There were rich and startling showers of meteors on November 12, 1799, and on November 12–13, 1833. H. A. Newton examined the literature of meteoric falls and found that many similar showers had been observed at intervals of thirty-three years running back several centuries, to 902 A.D., "the year of the stars," and he confidently predicted that another great shower would occur on November 13–14, 1866. His prediction was abundantly verified. Early in 1867 Schiaparelli and Le Verrier independently computed the orbit of these meteors, and Schiaparelli and Oppolzer independently found it identical with the orbit of the comet 1866I. Here are the elements of the two orbits:

Orbits of	Meteors of November 13	Comet 1866I
Perihelion passage	November 10.092	January 11.160
Longitude of perihelion	56° 25′.9	60° 28′.0
Ascending node	231 28 .2	231 26 .1
Inclination	17 44 .5	17 18 .1
Perihelion distance	0.9873	0.9765
Eccentricity	0.9046	0.9054
Semi-major axis	10.340	10.324
Period of revolution	33.250 years	33.176 years
Direction of motion	retrograde	retrograde

It is impossible to doubt that these November meteors and the comet referred to were traveling in the same orbit.

The so-called Lyra meteors are visible about April 20 each year. It was noticed in 1867 by Weiss that the orbit of the Lyra meteors is essentially identical with that of the comet 1861I.

Biela's comet, to which we have referred, when last seen in 1852, as a double comet, was expected to return in 1866 and again in 1872, but it was not seen then, nor later. A meteor shower of moderate intensity was observed on November 27, 1872, moving in the orbit of the lost comet.

Not to dwell upon the remarkable identities of the orbits of the four meteor swarms, respectively, with the orbits of the four comets (Fig. 14), two of which have disappeared, and the other two, of relatively long periods, which may never return, we express the prevailing opinion of astronomers in saying that the meteor streams have actually resulted from the disintegration of the four comets. Alexander Herschel has prepared a list of seventy-six meteor streams whose orbits agree fairly closely with seventy-six comet orbits. A certain proportion of the suspected identities probably represent facts. It is interesting to note that even as early as 1861 the truth of the situation was expressed and printed by Kirkwood:

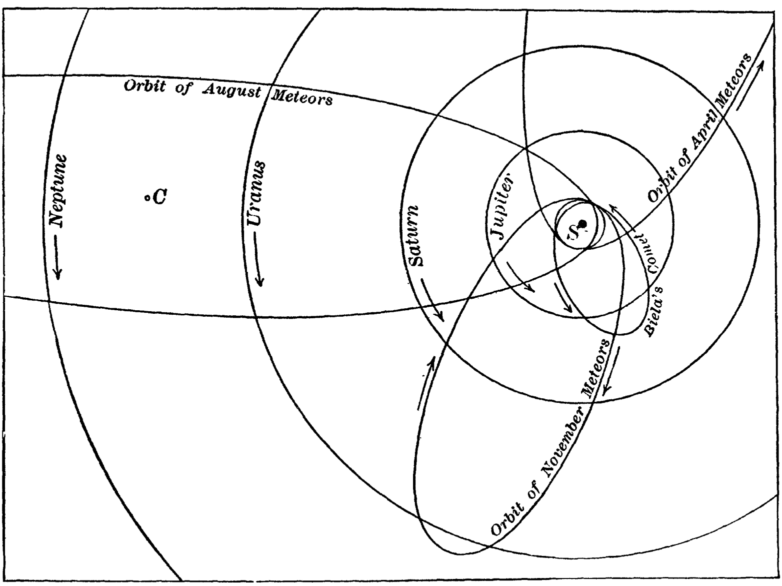

FIG. 14. ORBITS OF METEORIC SWARMS, which are known to be associated with comets.

> May not our periodic meteors be the debris of ancient but now disintegrated comets whose material has become distributed around their orbits?

It was in this connection and at that time that Kirkwood was able to make a list of eight comets, each of which had divided into two or more parts and had wholly disappeared from the sight of observers.

The cause of the disintegration of comets is not far to seek. A

comet's nucleus is thought to be a collection or cluster of small bodies, such as have been observed to collide with our atmosphere and to produce the meteor showers. They are held together, so to speak, while they are far away from the sun, because of their own very small but sufficient attraction for each other; but when they come within our planetary system, and especially when they come relatively close to the great planets Jupiter and Saturn, the sun and the planets attract the nearer particles of the comets more strongly than they do the farther particles. The nearer particles forge ahead on smaller orbits, the farther particles lag behind on larger orbits, and in the course of centuries the cometary material is strewn along a great stretch of the orbit. Other separative forces—of magnetic or electric natures, for example—may develop amongst the particles composing the nucleus as a comet approaches the sun. The intensity of the reflected light in all parts of the scattered comet structure becomes too small to let us see the remains of the comet, except as the remnants collide with the earth's atmosphere. There is certainly no reason to doubt that a very great many of our shooting stars are the remains of disintegrated comets. Tens of millions of little meteors enter our atmosphere every twenty-four hours and with rare exceptions are consumed by the heat of friction with the atmosphere when they rush through it at tremendous speeds. The gases from the combustion enter the atmosphere, and the ash and other unconsumed parts fall down to the earth's surface in due time. Accumulated meteoric dust is found in the perpetual snows at the tops of high mountains, and Sir John Murray found it in the ooze brought up from the depths of the oceans. Whether the meteorites which penetrate our atmosphere and are found and placed in our museums are parts of ancient comets can not safely be asserted, but it seems entirely possible that some of them are. However, it is not certain that any meteorite found on the earth has come from a meteor stream of recognized cometary origin. It is pretty well established that many of the sporadic meteors which plunge into our atmosphere were traveling on hyperbolic orbits.

We discover only a certain proportion of the comets which come close to the sun and to the earth. The numbers which course through the planetary system and remain undiscovered by the observers on the earth must be exceedingly great. The supply of cometary material in the remote outskirts of the planetary system must be enormous. This material is probably in the nature of remnants of the nebula or other mass of matter from which the sun, its planets and their moons developed. This idea is to a certain extent speculative; but that the cometary material is now out there in abundance we can not doubt. Much of it naturally consists of matter in the solid state; and, the sun's attraction at that great distance being almost zero, neighboring masses

could slowly come together as a collection of small solid masses, such as seem to compose the nucleus of a comet. Such a nucleus could attract and attach to itself any dust particles and molecules coming within its sphere of attraction. These might well, and probably would, include a collection of finely divided matter that had already been driven off in the tails of comets which in earlier ages had visited the sun. The materials thus collected would be attracted by the sun, a few of the collections would eventually pass comparatively close to the sun, a few of the latter would be discovered as comets, and a part of the finely divided material contained in them would be driven off again as comets' tails into space, possibly to return many times in the bodies of comets coming later into the sun's neighborhood. Certain of these bodies would come so close to the planets as to have their orbits transformed from very long ellipses to very short ellipses. These comets would be disintegrated and their materials be widely scattered. We have seen that the earth has collided with such materials, and the earth is growing slowly, very slowly, through the deposition of the remains upon its surface. Probably a little of the same materials goes likewise to other planets of the solar system and adds slowly to their masses. However, an insignificant proportion of the materials scattered in this manner through the solar system is thus accounted for, and the remainder doubtless revolves around the sun in ellipses, probably contributing its share of reflected sunlight to the faint glow near the sun known as the zodiacal light.

We have seen that devoted students of comets have learned much concerning these interesting travelers. Many mysteries have been removed, but many questions remain for the astronomers of the future to answer. We should especially like to know more of the physical conditions existing in comets, more about their chemical contents, and more as to why and how they shine by their own light. Perhaps the most valuable result of cometary investigation has been the emancipation of civilized peoples from unreasoning and groundless fears of these bodies, which come and go in obedience to the same simple laws that govern our every-day affairs.